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Assessment of the performance of the airflow in an operating theatre

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SUMMARY

Recently, a German draft standard that describes a method to assess the performance of an operating room ventilation system has been made available by the VDI [1].

To evaluate the VDI procedure and to assess practical problems, measurements have been performed in a full-scale mock-up of an operating theatre. In the design stage the VDI approach may also be useful for an objective design assessment. In that case the approach can be mimicked through the application of the Computational Fluid Dynamics (CFD) technique.

In this paper the results of the full scale measurements and a comparison with numerical results will be presented.

It is possible to use the VDI 2167 to evaluate the performance of a room in a reproducible manner. The CFD simulations underestimate the temperatures in the periphery of the room. A better prediction of these temperatures will lead to a better prediction of the particle concentration on the operating table.

INTRODUCTION

The main purpose of a ventilation system in an operating room is to keep the wound area free from contaminants. Modern systems use a laminar downflow. Clean air is supplied through the ceiling at a low speed, but over a large surface. If the system works well, this clean air reaches the wound area and the instrument tables without mixing with possibly contaminated air from the environment.

Previous research [2] [3] has shown that the difference between the inlet air temperature and the temperature of the air surrounding the clean area is of great importance. The inlet air temperature needs to be colder than the surrounding temperature. In that case the clean air is heavier than the surrounding air, and it will descend towards the patient and the instrument tables. If the temperature difference is too low, heat sources underneath the plenum can disturb the flow pattern. If the temperature difference is too high the velocity will increase, decreasing the size of the clean area. The larger velocity gradient at the edges of the clean area will cause more turbulence. This will mix relatively dirty air from the surrounding area into the clean area.

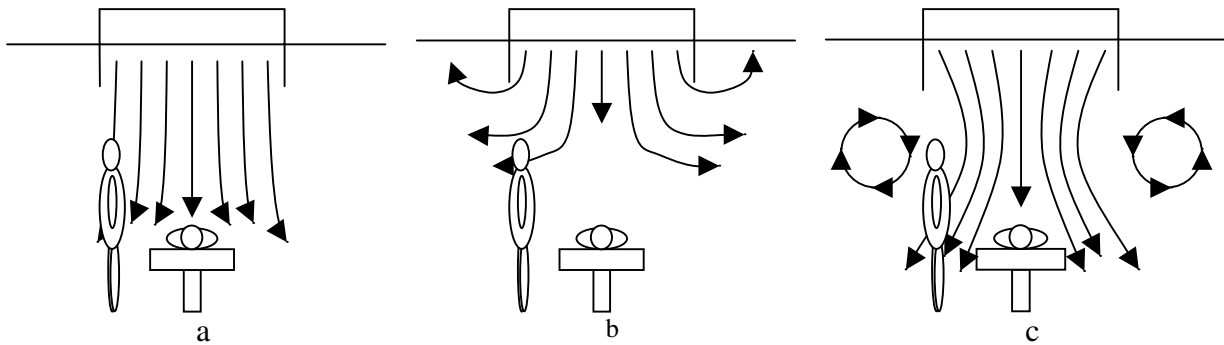


Figure 1. Example flow patterns. a) Good situation. b) Inlet air too warm. c) Inlet air too cold.

When a new operating room is designed, a lot of effort is being put in the properties of the ceiling inlet. In this process the furniture arrangement and equipment used need to be considered, as they influence the flow pattern in the room and thus influence the performance of the ventilation system.

As of recent, usage of Computational Fluid Dynamics (CFD)-calculation techniques is becoming commonplace in the design process of operating rooms. Using these techniques the air flow and temperature distribution in a room can be predicted before the room is built, thus making it possible to base design decisions on predicted flow conditions.

After a room is built, upon delivery, there are tests carried out. Mostly, these are tests to ensure that the filters are working properly and that the outflow is uniformly distributed over the ceiling. So, currently the tests focus on the specifications and performance of the components, not on the overall performance, i.e. clean air at the operating table. A new standard, VDI 2167 [1], is in production that responds to that. The current draft document describes a method for validating the performance of the complete system, including the amount of protection that the air flow pattern provides. This means that focus is on the performance at the operating table, and not at the supply. According to this standard, tests have to be carried out regularly.

The performance indicators used in the VDI 2167 are the particle concentration on the table, expressed in a protection class, and various parameters to determine the comfort of personnel. When these performance indicators are used to make design decisions, they need to be predicted with enough accuracy to justify the decisions. When design decisions are made by means of simulation results, the sensitivity of that simulation towards the performance indicators needs to be estimated. If the simulation is sensitive one should take more care of, e.g., the modelled geometry, boundary conditions or even the turbulence model applied. [4][5]

There were two goals in this project. The first one was to gain experience using the methods described in the VDI 2167. The other one was to assess the applicability of CFD simulation methods for assessing the performance of the ventilation system of an operating room according to VDI 2167. To do so, measurements have been taken in a full size operating room. CFD calculations were made of the same situation. The simulations results are compared to the measurements.

METHODS

Measurements have been performed in a full-scale mock-up of an operating room. Figure 2 presents a photograph of the investigated room. As supply, a downflow plenum was used, measuring 1.3 x 2.1 meter. The exhaust is divided over twelve outlets in the room. They are situated in the 4 corners, on three different heights.

There is an operating table in the middle of the room, directly underneath the plenum. Around the table are puppets. These are built from plastic cloth over a metal frame. Inside the frame are light bulbs to provide heat. The dimensions and placing of these puppets adhere to the VDI standard. An OR-lamp is present as well.



Figure 2. Puppets arranged according to the standard.

The measurements are divided into two different groups. The first group of measurements was used to record boundary conditions. These measurements are not required by the VDI 2167. They are done here strictly to provide boundary conditions for the simulations. They encompassed:

- Infrared photographs of walls, ceiling and floor.
- Exhaust air flow rates.
- Temperature of the inlet air.
- Air velocity at various points across the air inlet.
- Electrical power used by the puppets and the lamp.

The second group of measurements was done to record flow conditions in the room. When following the VDI approach, only a minimal set of measurements is required to determine the performance of the room. In addition to these we measured temperatures and air velocities in additional points inside the room. Purpose of these additional measurements is to gain better understanding of the processes that affect the clean area. The extra data points can be used in the comparison with the CFD simulations as well.

The measurements were performed in two sessions of 20 minutes. These measurements have been repeated the next day. Some sensors were relocated between the measurement series, others were kept in place and two sensors were swapped.

The test chamber that was used in the investigation is situated inside a production building. This building is lightweight and has no cooling itself. During the measurement period there was a heat wave. The test chamber itself does have moderately insulated walls. Therefore the temperature inside the room was much higher than usual in an operating room. However, this fact in principle does not affect the actual performance of the principle, as that is based on the temperature difference.

The particle measurements were done in a separate experiment. According to the VDI 2167 a particle generator should be used to generate a known constant stream of particles. These particles should be released equally distributed over 6 points around the table. As we did not have access to a particle generator, particles were generated using a smoke tube. The particle concentration was measured on various points on the operating table and at one of the air outlets. The particle counters measured the number of particles for each minute. After 10 minutes the particle concentrations had reached the background levels again.

Simulations

The CFD simulations were made by two different individuals, each using a different code. The software packages used were Phoenics [6] and Fluent [7]. Both simulations used up to 300.000 cells. A standard k- ϵ turbulence model and standard wall function, in combination with the energy equation (convective and radiant), were used to model the air flow. Boundary conditions for the walls were entered as fixed temperatures, puppets and equipment as fixed heat gains.

The measurements of boundary conditions and flow properties in the room show no large variation in time, so the problem is regarded steady state.

RESULTS

Measurements

The air temperature on all measuring points inside the clean area is just as low as the inlet air temperature (21.3 °C). Outside the clean area the temperature is higher than in the clean area. It ranges from 22.4 °C on the floor to 25.6 °C near the ceiling.

The velocity of the air at the inlet was 0.33 m/s on average. The highest air velocities were measured near the feet of the patient (0.40 m/s) and on the ground behind the feet of the patient (0.25 m/s). Air velocities around the clean area were generally under 0.20 m/s.

The particle measurements showed that, in this room and under these conditions, the head side of the table is cleaner than the middle of the table. The feet of the table collect the most particles. Some of the measurements were dropped because an insufficient number of particles were generated. Figure 3 shows a typical set of measurements.

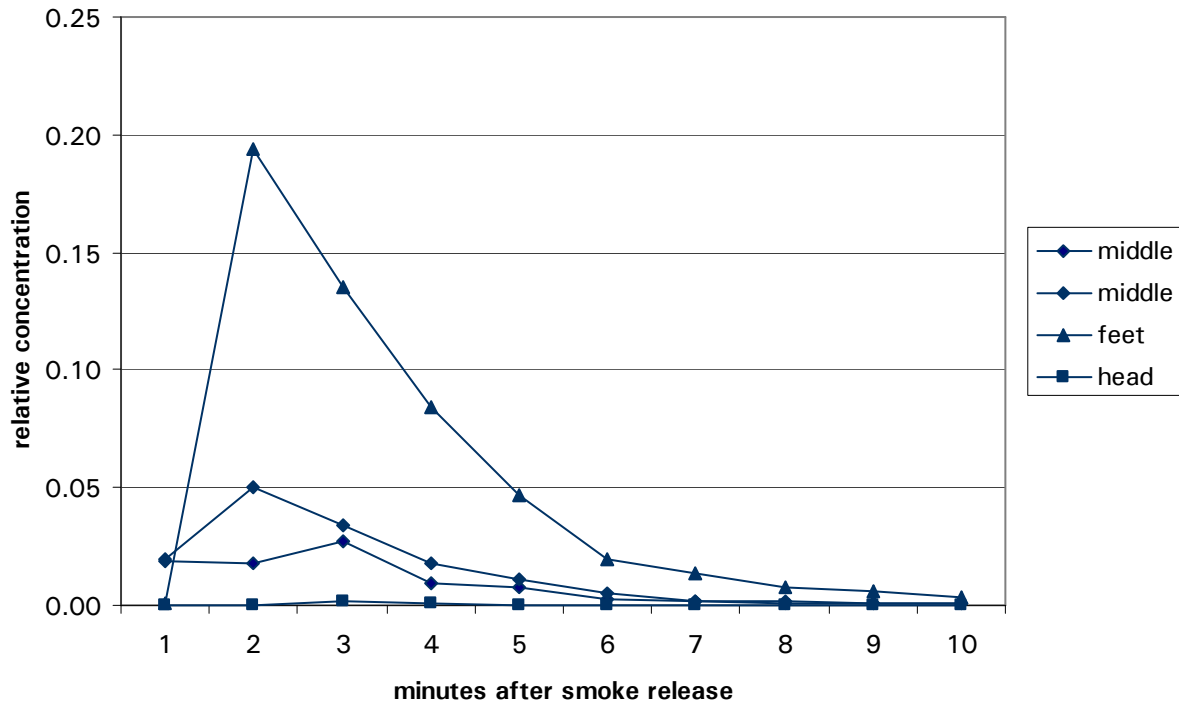


Figure 3. Example of results from particle measurements. The number of particles counted on the table for every minute divided by the total number of particles counted at the exit.

Simulations

The simulations were made by two different people using two different programs. When the simulations were compared, the temperature and velocity distribution showed good similarity. The air temperature under the plenum has the same value as the inlet temperature. The temperature in the surrounding area is about 1 °C higher than the inlet temperature.

The highest air velocities are predicted to be just over the edge of the operating table, near the head and the feet of the patient. The prediction of the particle concentrations were all lower than the measurements.

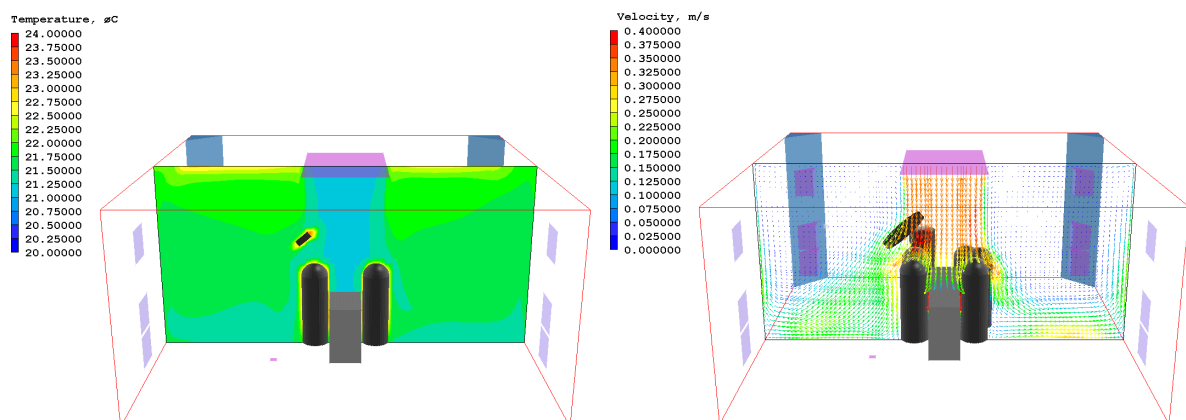


Figure 4. Temperature and flow distribution as produced in the simulation.

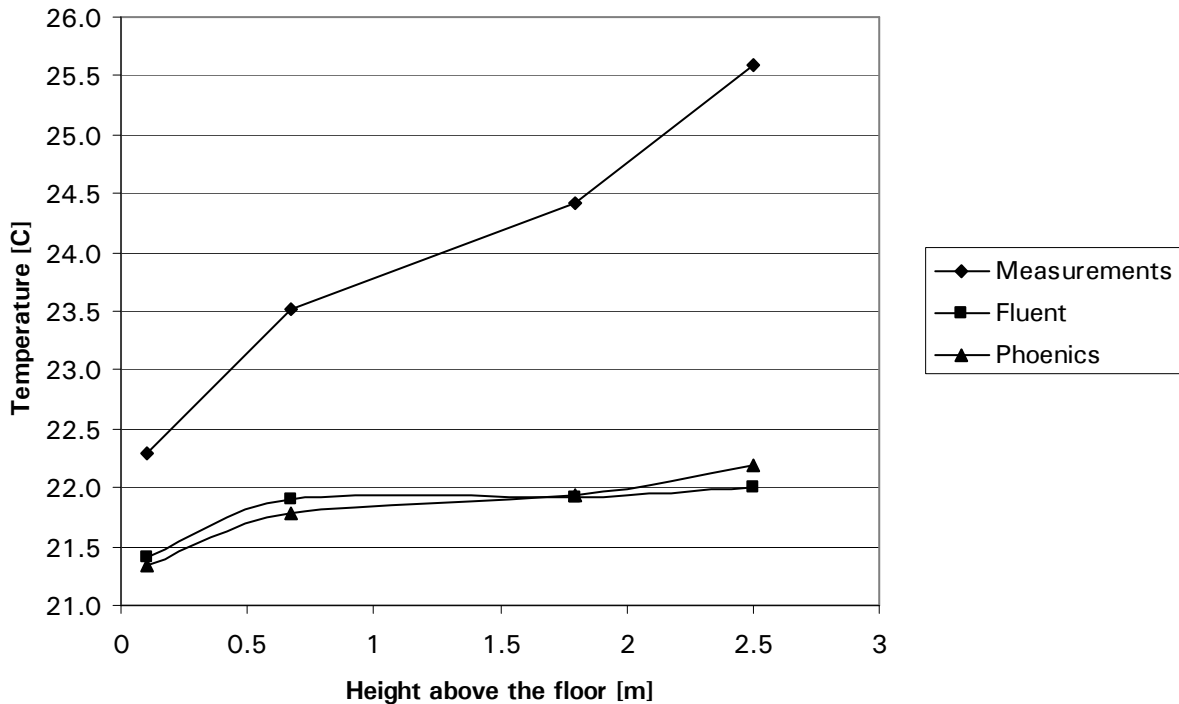


Figure 5. Average air temperatures in the periphery of the operating room as function of the height from the floor.

DISCUSSION

Using a smoke tube to generate particles has a few disadvantages. It is not possible to repeat the experiment as it is not possible to generate the same amount of smoke twice. It is however possible to compare the amount of particles counted on the table to the amount at the air outlet. Repeated experiments show that the ratio between the concentration on the table and the concentration at the outlet can be reproduced.

The fact that no proper particle generator was used to do the particle measurements means that we were unable to accurately determine the protection class of this particular plenum. Reproducibility of the relative concentration on the operating table indicates that measuring the protection class consistently is possible.

We measured the air temperature in the area underneath the plenum to be the same as the air temperature at the plenum. This is predicted well by the CFD programs. The air temperatures measured in the surrounding area were considerably higher than in the simulations. See figure 5. This causes a constriction of the air flow and thus a smaller clean area. This effect is shown in figure 1c.

The application of standard wall functions can be a considerable source of this inaccuracy [8]. Differences between the simulations and the measurements of the air temperature in the periphery might also be explained by the fact that the boundary conditions were not measured at the same moment as the flow conditions. To explain the inaccurate temperature prediction in the periphery further research is needed.

Some of the temperature and velocity measurements were taken in areas with a high gradient. This makes both measurements and simulations less accurate. An example is shown in figure 6.

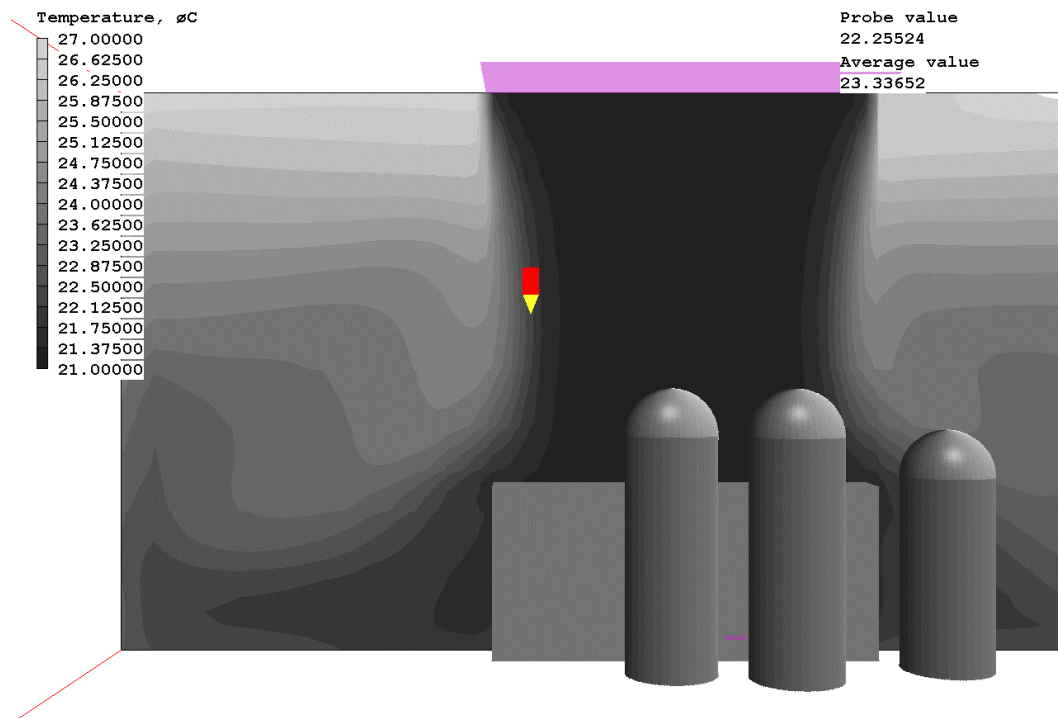


Figure 6. Air temperature distribution on the edge of the clean area near the feet of a patient. This figure shows the large gradient in which the measurements are taken. The arrow is one of the air temperature measurement points.

Particle concentration prediction

The predicted amount of particles on the table was far lower than the measurements. Therefore it can be concluded that the performed simulations would not have been a good substitute for the measurements.

The inaccurate results of the temperature in the simulations may have affected the accuracy of the airflow and particle distribution. Therefore an extra simulation was made to see what the consequence of higher room temperatures on the prediction of the particle concentration on the table is. To achieve higher temperatures the boundary conditions of the walls are changed from a fixed temperature to a fixed heat flux of 600 Watt for each wall. This resulted in a more accurate prediction of the air temperature and velocities in the room. The result of this extra calculation can be seen in figure 7.

The prediction of the particle concentration in the simulation with the heated walls is in most cases an order of magnitude more accurate than the simulation without the heated walls. Therefore it can be concluded that it is necessary to predict the indoor climate more accurately before a reliable prediction of the amount of particles that arrive on the table can be made.

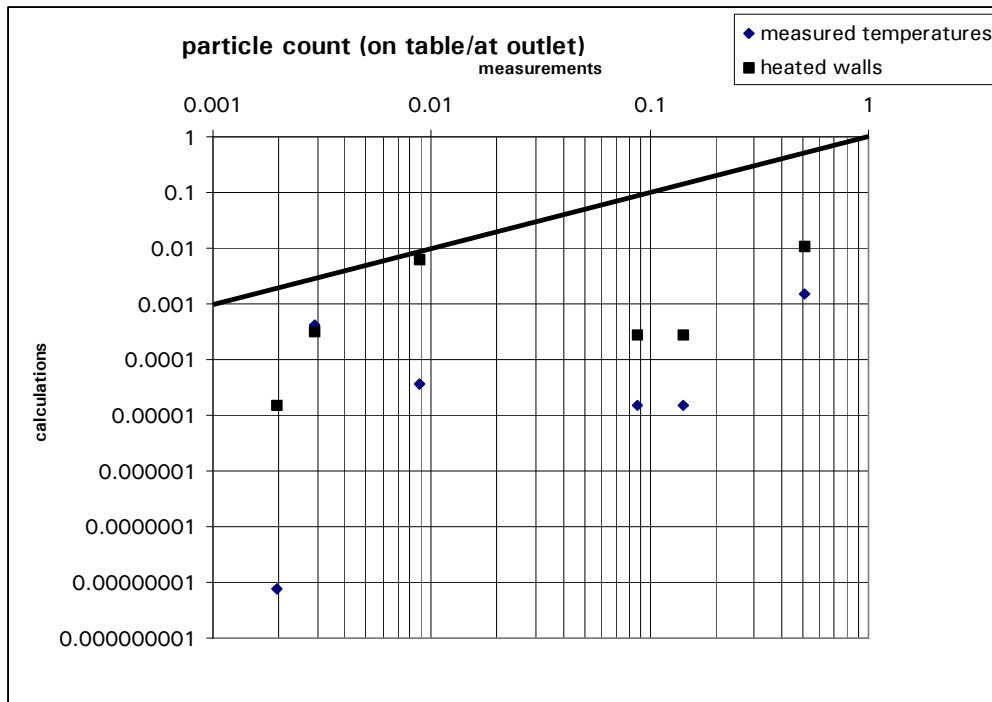


Figure 7. Particle concentration on the table divided by the concentration at the outlet.

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